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For: IMPROVED PLATE-FRAME HEAT EXCHANGE REACTOR WITH SERIAL CROSS-FLOW GEOMETRY

Enclosed are:

4 sheet(s) of drawings  
 Assignment and Cover Sheet  
 Information Disclosure Statement, PTO Form 1449, and Copies of Citations  
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## IMPROVED PLATE-FRAME HEAT EXCHANGE REACTOR WITH SERIAL CROSS-FLOW GEOMETRY

### Technical Field

The present invention relates generally to heat exchange systems and more particularly plate-frame heat exchangers.

### Background

Plate-frame heat exchangers are commonly employed to provide relatively compact devices with low-pressure drop. Such devices are typically deployed in weight/volume critical applications such as automotive air-conditioning evaporators, gas turbine recuperators, fuel cells, and liquid-liquid industrial heat exchangers. Because these applications are sensitive to both heat exchanger size and pressure drop through the fluid passages, typical plate-frame heat exchangers have a series of individual heat exchanger cells arrayed substantially in parallel (i.e. each cell (hot fluid side and cold fluid side) has the same temperature distribution as every other cell in the stack of cells comprising a completed heat exchanger)).

Because of the success of the plate-frame approach to heat exchanger design, it has been widely adapted to chemical reactions requiring temperature control, especially those that require close temperature control because of product selectivity or

are strongly endothermic or exothermic and require rapid heating and cooling.

A common example of considerable importance is steam reforming of hydrocarbons and alcohols (This reaction involves the reversible chemical conversion of methane and water into carbon monoxide and hydrogen). This reaction is highly endothermic, and typically requires large amounts of catalyst to promote the reaction. A complication of the use of the plate-frame reactors is that the effectiveness in exchanging heat between the cooler reformate stream and the hot combustion products plays a strong role in determining the thermal or thermodynamic efficiency of the reforming system. Effectiveness factor is defined as the temperature that occurs in the fluid undergoing the maximum temperature change divided by the difference between the highest and lowest temperatures in the heat exchanger.

Current technologies have focused on plate-frame reformers having an array of small reactors massively in parallel to each other. This design is far more compact, lighter and less expensive than tubular-type reformers which are common in the industry. However, such reformers have three major drawbacks.

First, massively parallel construction leads to low flow velocity (and corresponding Reynolds number) and low laminar flow. This drawback is critical because lower laminar flow reduces heat transfer rates and reduces reactant mixing in the reactor structures, which along with the Reynolds

number are factors in sizing the reformer. Hence, a lower Reynolds number requires a larger reformer, which adds to the cost of the reformer system.

Second, manifolding in the massively parallel  
5 construction may be fairly complex. This complexity  
may cause poor fluid distribution with "dead zones",  
where little flow occurs, which reduces heat exchange  
effectiveness.

Third, controlled internal release of any one  
10 reactant is very difficult as the short reaction zone  
is only accessible from either end of the plate. This  
point is particularly important if the heat exchanger  
structure is to be used as a catalytic burner.  
Catalytic burning on the heat exchanger walls improves  
15 heat transfer locally by obviating convective heat  
transfer from the gas phase to the wall because the  
catalysts are located on the wall itself.  
Unfortunately, if fuel or oxidant levels are not  
controlled, the catalytic burning can occur at too high  
20 a rate, causing local increases in metal temperature  
referred to as hot spots. Hot spots significantly  
weaken the structure and may cause mechanical failure.  
Because of this fact, systems with catalytic burning on  
the wall must use exotic materials and dilute  
25 combustion gases to lower temperatures to an acceptable  
level, which negatively impacts both cost and  
efficiency.

It is thus highly desirable to design a  
plate-frame reactor that combats the three critical  
30 drawbacks of the massively parallel system.

### **Summary of the Invention**

It is thus one object to create a novel method of arranging the elements of a plate-frame heat exchange reactor with serial cross-flow geometry.

The new arrangement has several advantages  
5 over the massively parallel reactor systems. First,  
the new arrangement increases the Reynold's number of  
the flows to greatly improve the heat transfer  
characteristics and reactant mixing characteristics of  
the reactor, thereby reducing the reactor size by half  
10 or more. Second, the new arrangement allows for  
constructing reactors where reactant addition is  
possible at many distributed points along the serial  
flow using simple mechanical features in order to  
control hot spots or other undesirable chemical  
15 reactions. Third, the new arrangement greatly  
simplifies manifolding of the flows and reduces the  
number of distinct components required in the heat  
exchanger. Fourth, the heat exchanger plate geometry  
is not constrained to long narrow ducts to create high  
20 aspect ratio counterflow designs.

Other objects and advantages of the present invention will become apparent upon considering the following detailed description and appended claims, and upon reference to the accompanying drawings.

#### **Brief Description of the Drawings**

Figure 1 is a perspective view of a fuel processing assembly with a plate-frame heat exchange reformer having serial cross flow geometry according to the present invention;

5                 Figure 2A is a header sheet for use in a preferred embodiment of the present invention;

                   Figure 2B is an interleaved sheet for use in a preferred embodiment of the present invention;

10                Figure 2C is an exploded view illustrating the stacking of the cells according to a preferred embodiment of the present invention;

15                Figure 2D is an exploded view illustrating the stacking of the cells, wherein the fin sheets have been added to the header sheets, according to a preferred embodiment of the present invention, wherein the fin sheets are placed into the header sheets;

                   Figure 3 illustrates the flow pattern of feed gas and burner exhaust utilizing serial cross flow through a plate frame reactor according to a preferred embodiment of the present invention;

                   Figure 4 illustrates the flow pattern of feed gas and burner exhaust utilizing purely serial cross flow through a plate frame reactor according to another preferred embodiment of the present invention; and,

25                Figure 5 illustrates the flow pattern of feed gas and burner exhaust utilizing a combination of

serial cross flow and parallel flow through a plate frame reactor according to another preferred embodiment of the present invention.

#### Description of the Preferred Embodiment(s)

Referring now to Figure 1, a fuel processing assembly 10 which forms a portion of a typical fuel cell power plant is depicted. The assembly 10 includes a plate frame heat exchange reformer 12 for converting hydrocarbon fuels into hydrogen that is used by electrochemical fuel cells (not shown) to generate electricity. The reformer 12 is primarily comprised of a series of stacked cells 14. Each stacked cell 14 is comprised of a header sheet 16 and an interleaved sheet 18. The reformer 12 has an intake port 20 for receiving feed gas, typically gasoline, natural gas, or some other type of hydrocarbon, from a reservoir (not shown) and an outlet port 22 for removing the heated reformed feed gas from the reformer 12. The feed gas may also comprise any combination of water, oxygen, nitrogen, carbon monoxide, carbon dioxide, hydrogen, and partially reacted fuel. The reformer 12 has a burner inlet port 24 for receiving heated burner exhaust gas and/or a partially or wholly unreacted mixture of fuel and oxidant (hereinafter referred to as burner exhaust gas) and a burner outlet port 26 for removing cooled burner exhaust gas from the reformer 12. The flows of the feed gas and burner exhaust through the embodiments of the present invention are described in more detail below.

Figure 2A illustrates a header sheet 102 according to a preferred embodiment of the present

invention having a central zone 106, a fin sheet 108, and a series of manifold ports 110. The central zone 106 houses the fin sheet 108 or roll-formed fins that form the extended heat transfer surface. The fin  
5 sheets 108 may contain louvres 121 or other features to control the flow across their surfaces as is known in the art. While the preferred embodiment depicts fin sheets 108, it is contemplated that other types of heat transfer surfaces, such as pin fins, metal foam, or  
10 corrugated sheets may be used as heat transfer components. The header sheet 102 may also contain a locator tab 114. While not depicted in Figure 2A, the manifold ports 110 may be on any or all sides of the header sheet 102. As shown in Figure 3 below, they  
15 will be depicted as 110f representing manifold ports located on the front side 102f of the header sheet 102, 110l for the ports located on the left side 102l of the header sheet, 110r for ports located on the right side 102r of the header sheet, and 110b for ports located on  
20 the back side 102b of the header sheet 102. Further, the number and size of manifold ports 110f, 110r, 110l and 110b may vary according to the flow strategy of the system that they are used in. In addition, these manifold ports 110 may be augmented by similar passages  
25 (not shown) for the conveyance of yet additional reactant fluids or diluents.

Figure 2B illustrates the thinner interleaved sheet 120 according to a preferred embodiment of the present invention. The interleaved sheets 120 form the common heat transfer interface between the fluids. The interleaved sheet 120 may also contain a locator tab 126. Similar to the header sheets 102, the interleaved  
30

sheets 120 contain interleaved manifold ports 122. While not depicted in Figure 2A, the interleaved manifold ports 122 may be located on any or all sides of the interleaved sheet 120. As shown in Figure 3, 5 the interleaved sheets 120 may have front side interleaved manifold ports 122f, right side interleaved manifold ports 122r, left side interleaved manifold ports 122l, and/or back side interleaved manifold ports 122b. Further, the number and size of the interleaved 10 manifold ports 122r, 122f, 122l, and 122b may vary according to the flow strategy of the system they are placed in. Finally, the interleaved sheets may contain louvres 121 or other features to control the flow across their surfaces as is known in the art.

15                 Figure 2C and 2D illustrate an exploded view of alternating copies of the header sheet 102 and interleaved sheet 120 of Figures 2A and 2B. Each pair of header sheets 102 and interleaved sheets 120 form a single cell 104. The assembly of a purely serial flow 20 heat exchanger 100 reactor from the bottom would proceed by rotating subsequent sets of header sheets 102 and interleaved sheets 120 90 degrees counterclockwise from the previous pair. For simplicity, note the location of the locator tab 114 of 25 the header sheet 102 relative to the location of the locator tab 126 of the interleaved sheet 120 in a single cell 104. Figure 2D illustrates the fin sheets 108 contained within the central zone 106 of the header sheet 102.

30                 The header sheets 102 and interleaved sheets 120 may be joined through many techniques that are well

known in the art, including soldering, brazing, and adhesive joining. For high temperature applications, brazing is the preferred method.

A catalyst material (not shown) may be  
5 affixed to the reactor 100 by applying a thin layer of  
catalytic material to the structural substrate  
material. This might comprise a layer of high surface  
area gamma-alumina powder with a dispersed catalytic  
metal adhered to a superalloy or stainless steel  
10 structure. The open manifolds 110, 122 possible in the  
serial flow design allow for uniform application of  
such "washcoat" catalyst layers because they allow  
uniform access to the complex fin sheets 108 upon which  
the bulk of the catalyst is disposed. Methods of  
15 applying such catalyst layers are well known in the  
art.

Referring now to Figure 3, the flow patterns  
of feed gas and burner exhaust through the reformer 100  
having purely serial flow geometry according to a  
20 preferred embodiment is depicted.

Cool feed gas enters the reformer 100 through  
an inlet port 101, or plenum. The feed gas then  
proceeds between a top sheet 117 and top header sheet  
102a within a topmost cell 104a that defines a first  
25 reformer section 103a. The top sheet 117, as depicted,  
is a sealing sheet and contains no manifold ports.  
However, the top sheet 117, in alternative embodiments,  
could contain the inlet port 101. The feed gas then  
enters front manifold port 110f, flows through the  
30 front interleaved manifold port 122f of the interleaved  
sheet 120. The feed gas then flows back through the

next adjacent reformer section 103 to back manifold port 110b, flows through back manifold port 110b and back interleaved manifold port 122b and into the next adjacent reformer section 103. The feed gas then flows  
5 back through the next adjacent reformer section 103, enters the front manifold ports 110f, flows through front interleaved manifold 122f, and into the next adjacent reformer section 103. This process continues through the stack of reformer sections 103 until the  
10 heated and fully reacted feed gas reaches the outlet port 105. The number of cells 104 in the reformer 100 may vary greatly depending upon the requirements of the system. For example, flow rate, catalyst activity, and peak temperature are factors in determining the number  
15 of cells 104 within the reformer 100.

At the same time, heated burner exhaust enters the reformer 100 through a burner inlet port 107. The burner inlet port 107 is located at the bottommost cell 104b, while the feed gas inlet port 101  
20 is located at the topmost cell 104a. Of course it is understood that the opposite could be true, wherein the feed gas inlet port 101 is located in the bottommost cell 104b and the burner inlet port 107 is located in the topmost cell 104a.

25 The burner exhaust flows through a first burner section 105a as defined between a bottom section 109 a bottom sheet 102b. The exhaust then enters the left manifold ports 110l, flows through left interleaved manifold ports 122l, and into the next adjacent burner section 105. The exhaust then flow  
30 through the next adjacent burner section 105 and into

the right manifold port 110r, through the right interleaved manifold port 122r and into the next adjacent burner section 105. This process continues through the stack of burner sections 105 until the  
5 cooled exhaust gas reaches the burner outlet port 111.

As seen in Figure 3, the flow patterns of the feed gas and the burner exhaust flow flowing through adjacent reformer sections 103 and burner sections 105 are locally perpendicular with respect to each other,  
10 although the overall flow geometry is counterflow. This is known as serial cross-flow geometry. In addition, heat is exchanged through the interleaved-sheets 120. In this way, the feed gas is heated and eventually reacted and the burner exhaust gas is cooled  
15 within the reformer 100. To aid in the heat exchange, the interleaved sheets 120 may be provided with heat transfer enhancement in the form of louvres 121 or separate fin sheets 108.

In addition, a second inlet port 180 may be  
20 added to direct a secondary flow of feed gas into the reformer 100. The second inlet port 180 is added between one of the header sheets 102 and one of the interleaved sheets 120 defining a cell 104 and introduces feed gas to the reformer section 103.  
25 Similarly, a second burner inlet port 190 can be added to direct a secondary flow of burner exhaust gas, fuel, oxidant, or diluent into the burner section 105. In this way, the heat exchange, and corresponding chemical reaction in the reformer section 103 and burner section  
30 105, can be more closely controlled in order to avoid hot spots and limit unwanted chemical reactions. Of

course, the number of second inlet ports 180 and second outlet ports 190 may be increased beyond the two depicted in Figure 3 depending upon the requirements of the system.

5           In another preferred embodiment of the present invention, as depicted in Figure 4, a reformer 200 is illustrated having serial parallel flow with two cells in parallel. The locally perpendicular flow of feed gas and exhaust gas flows similarly to the  
10 reformer 100 of Figure 3, but instead of every other cell having reformer sections and burner sections with different flow directions and temperature-distributions, the cells are paired in groups of two, each having substantially identical flow directions and  
15 temperature distributions.

          Cool feed gas enters the top of the reformer 200 at a pair of inlet ports 201a, 201b defining inlet port 201. The feed gas entering through inlet port 201a flows between a top sheet 217 and a first header sheet 202a which defines a first reformer section 203a. Feed gas flows through the first reformer section 203a and into the front manifold ports 210f, through a front interleaved manifold port 222f of a adjacent interleaved sheet 220, through a front manifold ports 210f of the next adjacent header sheet 202, and through a front interleaved manifold port 222f of the next interleaved sheet 220 and into a reformer section 203. The feed gas then flows through the reformer section 203c and into a rear manifold port 210b, through a rear interleaved manifold port 222b, through another rear manifold port 210b, and through another rear

interleaved manifold port 222b to reach the next reformer section 203e. The process continues based on the flow requirements of the system until it reaches a feed gas outlet port 205a.

5 At the same time, a second quantity of cool feed gas flows from inlet port 201b between the first header sheet 202a and the first interleaved sheet 220a that defines a second reformer section 203b. The second quantity of cool feed gas then flows through a  
10 front interleaved manifold port 222f of the first interleaved sheet 220a, through a front manifold ports 210f of the next adjacent header sheet 202, through a front interleaved manifold port 222f of the next adjacent interleaved sheet 220, and through a front manifold port 210f and into a reformer section 203d.  
15 The feed gas flows through reformer section 203d, through a rear manifold port 210b, through a rear interleaved manifold port 222b, through a rear manifold port 210b or the next adjacent interleaved sheet 202,  
20 through a rear interleaved manifold port 222b of the next adjacent interleaved manifold sheet 220, and into the next adjacent reformer section 203f. Depending upon the flow requirements of the system, the first and second quantity of feed gas may intermingle between the  
25 reformer sections 203a, 203b respectively by being injected into the same manifold ports 210 or interleaved manifold ports 220. Similarly, the feed gas could intermingle between reformer sections 203d and 203e, respectively, and every next adjacent pair  
30 thereafter. The flow process continues until the feed gas reaches feed gas outlet port 205b. Feed gas outlet port 205a and 205b define feed gas outlet 205, which

discharges heated reformed feed gas from the reformer 200.

At the same time cool feed gas is introduced through feed gas inlet port 201, heated burner gas is 5 being introduced to the reformer 200 at burner gas inlet port 207. A first quantity of heated burner exhaust gas or partially or fully unreacted fuel and oxidant enters burner inlet port 207a between bottom sheet 209 and header sheet 202b, which defines a first 10 burner section 213a. The heated burner gas flows across burner section 213a and enters left manifold port 210l, goes through left interleaved manifold port 222l, through left manifold port 210l of an adjacent header sheet 202, and through a left interleaved 15 manifold port 222l of the adjacent interleaved sheet 220 and into the next burner section 213c. The burner gas then flows across the burner section 213c and enters right manifold port 210r, through right interleaved manifold port 222r, through right manifold port 210r, and through right interleaved manifold port 20 222r and into the next adjacent burner section 213f. This process continues until the burner gas reaches outlet port 211a.

At the same time, a second quantity of heated 25 burner gas enters burner inlet port 207b and into burner section 213b defined by header sheet 202b and interleaved sheet 220. The burner gas proceeds through burner section 213b and enters the left interleaved manifold port 220l, through left manifold port 210l, 30 through left interleaved manifold port 220l of the next adjacent interleaved sheet 220, and through left

manifold port 210l of the next adjacent header sheet  
202 and into the next adjacent burner section 213d.  
The burner exhaust flows through the burner section  
213d and into the right interleaved manifold port 222r,  
5 the right manifold port 210r, the next right  
interleaved manifold port 222r, and the next manifold  
port 210r and into the next burner section 213f. The  
process continues until the second quantity of burner  
gas reaches burner outlet port 211b. Outlet ports 211a  
10 and 211b form burner outlet port 211, which discharges  
cooled burner exhaust from the reformer 200.

It is contemplated that the first quantity of  
burner gas and the second quantity of burner gas may  
intermingle between burner sections 213a, 213b by using  
15 the same manifold ports 210, 222 located along the  
various sides of the header sheets 202 and interleaved  
sheets 220. Similarly, the reformer gas could  
intermingle between reformer sections 203d and 203e,  
respectively, and every next adjacent pair thereafter.

20 Further, it is contemplated in another  
preferred embodiment not depicted here that the serial  
cross-flow geometry could vary between 3, or even 4  
sets of sheets or more depending upon the flow  
characteristics desired within the reformer, thereby  
25 reducing the peak Reynold's number. In addition, it is  
contemplated that the reformer could use a combination  
of embodiments as depicted in Figures 3 and 4, wherein  
the zones used within the reformer are varied between  
single zones of cross flow, as in Figure 3, and paired  
30 zones, as in Figure 4. Again, the specific combination

of these zones would depend upon the desired characteristics of the system.

Referring now to Figure 5, another embodiment of the present invention is depicted. In this 5 embodiment, a reformer 300 is depicted having a mixture of serial flow zone reformers 301 and parallel flow zone reformers 302. The serial flow zone reformers 301, for example, may be similar to reformer 100 from Figure 3 or reformer 200 from Figure 4, and is depicted 10 similar to reformer 100 for representative purposes in Figure 5. In the parallel-flow zone reformer 302 portion, a feed gas inlet port 304a and a feed-gas-outlet port 306a are introduced at opposite ends between the bottom sheet 309 of the serial cross-flow reformer 301 and a first header sheet 311a of parallel-flow reformer 302. A burner gas inlet port 308a and burner gas outlet port 310a is introduced between the 15 first header sheet 311a and an interleaved sheet 313a.

Another feed gas inlet port 304b and feed gas outlet port 306b may be introduced between interleaved sheet 313a and the next adjacent header sheet 311, while another burner gas inlet port 308b and burner gas outlet port 310b may be introduced between header sheet 311 and the next adjacent interleaved sheet 313. In 20 this way, a reformer 300 can have mixtures of serial cross-flow and parallel-cross flow.

The exact mix of serial 301 and parallel zones 302 within reformer 300 would depend upon optimization based upon the system being investigated. 25 Systems where exchanger mass, volume, and cost

predominate would tend to have a more highly serial architecture.

Plate-frame heat exchange reactors with serial cross-flow geometry according to the present 5 invention offers many advantages over traditional massively parallel units.

First, the present invention allows for tailoring the Reynold's number of the flow to greatly improve the heat transfer and/or mass transfer 10 characteristics of the reactor. This allows reactor size to be reduced by half or more, resulting in substantial savings in weight, volume, and cost.

Second, the present invention allows for the possibility of introducing reactants at many 15 distributed points, rather than only at the entry point in massively parallel designs, using a simple mechanical feature added to the header sheets. This controls the formation of hot spots within the reactor that could lead to undesirable chemical reactions.

Third, the present invention offers greatly simplified manifolding of the flows and reduces the number of distinct components required for the heat exchanger. This results in substantial cost savings as compared with massively parallel designs.

Fourth, the heat exchanger plates are not constrained by a desire to create a high aspect ratio, perfect counterflow ratio in a single cell.

The application of the present invention is ideally suited for reaction systems where current,

massively parallel plate frame reactors are inadequate. One example is steam reforming of hydrocarbons or alcohols where reactor size is principally determined by heat transfer, and where controlled release of  
5 oxidant can greatly reduce the risk of hot spot formation. Another example is the preferential oxidation of carbon monoxide where close control of temperature, controlled oxidant release, and improved mass transfer are desired.

10 While the invention has been described in terms of preferred embodiments, it will be understood, of course, that the invention is not limited thereto since modifications may be made by those skilled in the art, particularly in light of the foregoing teachings.

**What Is Claimed Is:**

1. A plate frame heat exchange reactor assembly comprising:
  - a plurality of header sheets, each of said plurality of header sheets having a plurality of manifold ports;
  - 5 a heat transfer surface contained within a central region of each of said plurality of header sheets;
  - 10 a plurality of interleaved sheets, one of said plurality of interleaved sheets being located between each adjacent pair of said plurality of header sheets, wherein each of said plurality of interleaved sheets having a plurality of interleaved manifold ports;
  - 15 one of said plurality of interleaved sheets and an adjacent one of said plurality of header sheets defines a cell;
    - a feed gas inlet manifold port for directing a feed gas into the assembly;
  - 20 a burner feed inlet manifold port for directing a burner feed gas into the assembly;
  - 25 a reformer section coupled to said feed gas inlet manifold port so as to receive a stream of feed gas from said feed gas inlet manifold, said reformer section converting said stream of feed gas to a stream of reformed stream gas, said reformer section having a plurality of reformer channels, each of said reformer channels being formed between every other of said cells, wherein each of said reformer channels is coupled to said adjacent reformer channel through at least one of said plurality of manifold ports and at

least one of said plurality of interleaved manifold ports;

5 a burner gas section coupled to the burner feed inlet manifold so as to receive heated burner exhaust, said burner gas section having a plurality of burner channels, each of said burner channels being formed between the other of every other of said cells, wherein each of said burner channels is coupled to said adjacent burner channel through one of said plurality 10 of interleaved manifold ports and one of said plurality of manifold ports;

an outlet manifold coupled to said reformer section for removing reformed feed gas from the assembly;

15 a burner outlet manifold coupled to said burner section for removing cooled burner exhaust from the assembly; and,

20 wherein said feed gas flow and said exhaust burner gas flow is substantially perpendicular with respect to one another between a pair of adjacent cells and wherein said feed gas flow and said exhaust gas flow are substantially cross-flow with respect to one another in said reformer section and said burner section.

25 2. The assembly of claim 1, further comprising a second inlet manifold port coupled to one of said reformer channels between one of said plurality of header sheets and one of said plurality of interleaved sheets.

30 3. The assembly of claim 1, wherein a thin layer of catalyst is coated on each of said heat

transfer surfaces and on each of said plurality of interleaved sheets.

4. The assembly of claim 3, wherein said thin layer of catalyst comprises a layer of  $\gamma$ -alumina powder with a dispersed catalytic metal adhered to a superalloy.

5. The assembly of claim 3, wherein said thin layer of catalyst comprises a layer of  $\gamma$ -alumina powder with a dispersed catalytic metal adhered to a  
10 stainless steel structure.

6. The assembly of claim 1, wherein each of said header sheets are brazed to each of said adjacent interleaved sheets.

7. The assembly of claim 1 further  
15 comprising at least one parallel zone interspersed within the assembly, said at least one parallel zone comprising:

at least one second reformer section coupled to a third inlet manifold port so as to receive a third  
20 stream of feed gas from said feed gas inlet manifold port, said at least one second reformer section converting said third stream of feed gas to a third stream of reformed stream gas, each of said at least one second reformer section having a second reformer channel, each of said second reformer channels being formed between one of a plurality of second header sheets and an adjacent one of said plurality of second interleaved sheets, wherein said second reformer channel is connected to said outlet manifold; and

at least one second burner gas section coupled to said burner feed inlet manifold so as to receive a second stream of burner feed gas, each of said at least one second burner gas sections having a  
5 second burner channel formed between one of said plurality of second header sheets and the other adjacent one of said plurality of second interleaved sheets, wherein each of said second burner channels is coupled to said burner outlet manifold;

10 wherein the flow of said third stream of feed gas and the flow of said second stream of burner feed gas through said at least one parallel zone are substantially parallel and either in a co-flow or counterflow configuration with respect to one another.

15 8. A plate frame heat exchange reactor assembly comprising:

a plurality of header sheets, each of said plurality of header sheets having a plurality of manifold ports;

20 a heat transfer surface contained within a central region of each of said plurality of header sheets;

25 a plurality of interleaved sheets, wherein one of said plurality of interleaved sheets being located between each adjacent pair of said plurality of header sheets, each of said plurality of interleaved sheets having a plurality of interleaved manifold ports;

30 wherein one of said plurality of interleaved sheets and an adjacent one of said plurality of header sheets defines a cell;

a feed gas inlet manifold port for directing a feed gas into the assembly;

a burner feed inlet manifold port for directing a burner feed gas into the assembly;

5               a reformer section coupled to said feed gas  
inlet manifold port so as to receive a stream of feed  
gas from said feed gas inlet manifold, said reformer  
section converting said stream of feed gas to a stream  
of reformed stream gas, said reformer section having a  
10 plurality of reformer channels; ,

wherein at least two of said plurality of reformer channels are coupled together to form a coupled reformer channel, wherein each of said coupled reformer channels is coupled to the next adjacent one of said coupled reformer channels through at least one of said plurality of manifold ports and at least one of said plurality of interleaved manifold ports;

a burner gas section coupled to the burner feed inlet manifold so as to receive heated burner exhaust, said burner gas section having a plurality of burner channels;

wherein at least two of said plurality of burner channels are coupled together to form a coupled burner channel, wherein each of said coupled burner channels is coupled to the next adjacent one of said plurality of manifold ports and at least one of said plurality of interleaved manifold ports;

an outlet manifold coupled to said reformer  
30 section for removing reformed feed gas from the assembly;

a burner outlet manifold coupled to said burner section for removing cooled burner exhaust from the assembly;

wherein said feed gas flow in said coupled reformer channel and said exhaust burner gas flow in said next adjacent coupled burner channel are substantially perpendicular with respect to one another;

wherein said feed gas flow in said coupled reformer channel and said feed gas flow in a next adjacent of said coupled reformer channels flow in opposite directions with respect to one another; and

wherein said burner gas flow in said coupled burner channel and said burner gas flow in a next adjacent of said coupled burner channels flow in opposite directions with respect to one another;

wherein said feed gas flow and said exhaust gas flow are substantially cross-flow with respect to one another in said reformer section and said burner section.

9. The assembly of claim 8, further comprising a second inlet manifold port coupled to one of said reformer channels between one of said plurality of header sheets and one of said plurality of interleaved sheets.

10. The assembly of claim 8, wherein a thin layer of catalyst is coated on each of said heat transfer surfaces and on each of said plurality of interleaved sheets.

11. The assembly of claim 10, wherein said thin layer of catalyst comprises a layer of  $\gamma$ -alumina powder with a dispersed catalytic metal.

12. The assembly of claim 10, wherein said  
5 thin layer of catalyst comprises a layer of  $\gamma$ -alumina powder with a dispersed catalytic metal adhered to a stainless steel structure adhered to a superalloy.

13. The assembly of claim 8, wherein each  
of said header sheets are brazed to each of said  
10 adjacent interleaved sheets.

14. The assembly of claim 8 further comprising at least one parallel zone interspersed within the assembly, said at least one parallel zone comprising:

15 at least one second reformer section coupled to a third inlet manifold port so as to receive a third stream of feed gas from said feed gas inlet manifold port, wherein said at least one second reformer section converting said third stream of feed gas to a third stream of reformed stream gas, each of said at least one second reformer section having a second reformer channel, each of said second reformer channels being formed between one of a plurality of second header sheets and an adjacent one of said plurality of second interleaved sheets, wherein said second reformer channel is connected to said outlet manifold;  
20 at least one second burner gas section coupled to said burner feed inlet manifold so as to receive a second stream of burner feed gas, each of said at least one second burner gas sections having a  
25

second burner channel formed between one of said plurality of second header sheets and the other adjacent one of said plurality of second interleaved sheets, wherein each of said second burner channels is  
5 coupled to said burner outlet manifold; and  
wherein the flow of said third stream of feed gas and the flow of said second stream of burner feed gas through said at least one parallel zone are substantially parallel and either in a co-flow or  
10 counterflow configuration with respect to one another.

15. A method for optimizing heat transfer, mass transfer and pressure drop in a plate-frame heat-exchange reactor having an feed gas inlet manifold for receiving a stream of feed gas, a reformer section connected to the feed gas inlet manifold for converting the feed gas to a reformed feed gas, a feed gas outlet manifold coupled to the reformer section for expelling a stream of reformed feed gas, a burner inlet manifold for receiving burner exhaust, a burner section coupled  
20 to the reformer section for cooling the burner exhaust, and a burner outlet manifold for expelling the cooled burner exhaust, the method comprising the steps of:

increasing flow velocity of the feed gas within the plate-frame heat exchange reactor;  
25 increasing laminar flow of the feed gas within the plate-frame heat exchange reactor.

16. The method of claim 15 further comprising the step of:  
introducing a second quantity of feed gas at  
30 a first position within the plate-frame exchange reactor, wherein said first position is located between

the feed gas intake manifold and the feed gas outlet manifold.

17. The method of claim 15, wherein the steps of increasing flow velocity of the feed gas 5 within the plate-frame heat exchange reactor and increasing laminar flow of the feed gas within the plate-frame heat exchange reactor comprises the step of:

coupling the reformer section and the  
10 adjacent burner section such that the flow of feed gas through said reformer section and the flow of burner exhaust through in said adjacent burner section are substantially perpendicular with respect to one another, wherein the overall flow between said reformer section and said burner section is substantially serial  
15 counterflow.

18. The method of claim 15, wherein the steps of increasing flow velocity of the feed gas within the plate-frame heat exchange reactor and increasing laminar flow of the feed gas within the plate-frame heat exchange reactor comprises the steps of:

coupling a plurality of reformer sections to  
25 form a coupled reformer section;

coupling a plurality of burner sections to  
form a coupled burner section;

coupling said coupled reformer section and  
said coupled burner section such that the flow of feed  
gas through said coupled reformer section and the flow  
30 of burner exhaust through said next adjacent coupled  
burner exhaust section are substantially perpendicular

with respect to one another, wherein the overall flow between said plurality of coupled reformer sections and said plurality of coupled burner sections is substantially serial counterflow.

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**Abstract Of the Disclosure**

A plate-frame heat exchange reactor having a serial cross-flow geometry. This is accomplished by designing a plate-frame heat exchanger wherein the flow of feed gas in one cell of the reactor flows perpendicular to the flow of burner exhaust within the next adjacent cell. The improved reactor increases the Reynold's number of the flows as compared with a massively parallel design to improve heat transfer and reactant mixing characteristics, thereby reducing reactor size by half or more. The serial cross-flow arrangement allows for constructing reactors where feed gas addition is possible at many distinct points along the serial flow in order to control hot spots or other undesirable chemical reactions. The new arrangement also greatly reduces manifolding of the flows and reduces the distinct components of the reactor.

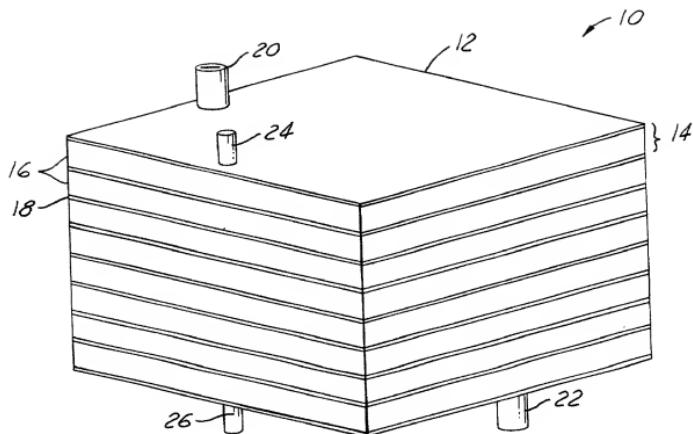


FIG. 1

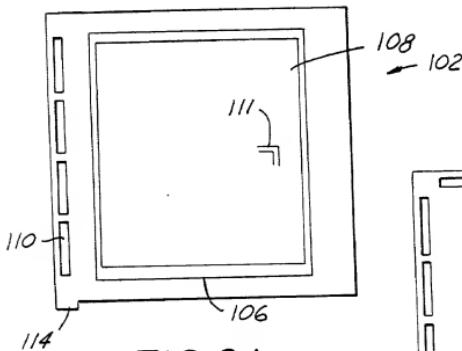


FIG. 2A

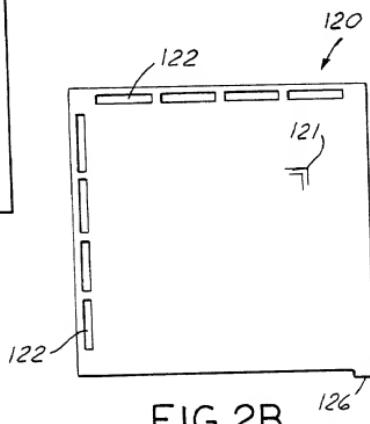


FIG. 2B

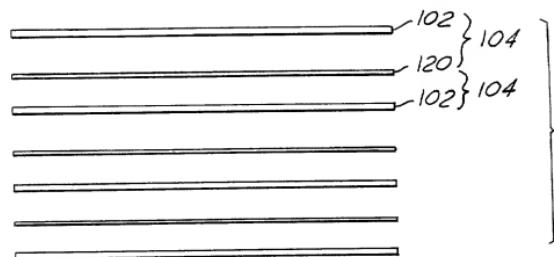


FIG.2C

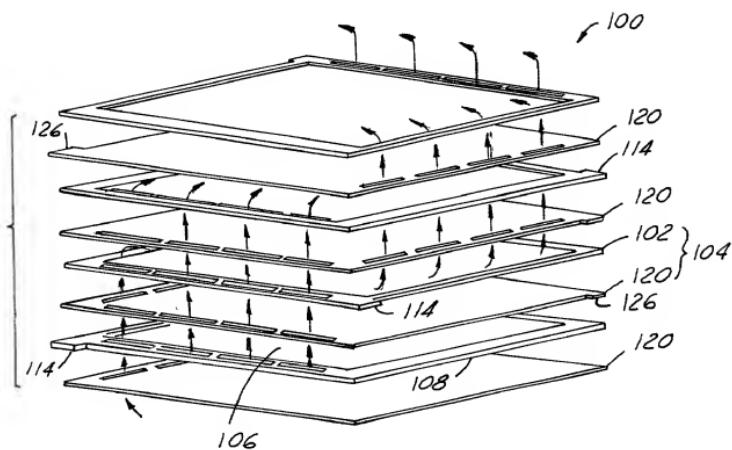


FIG.2D

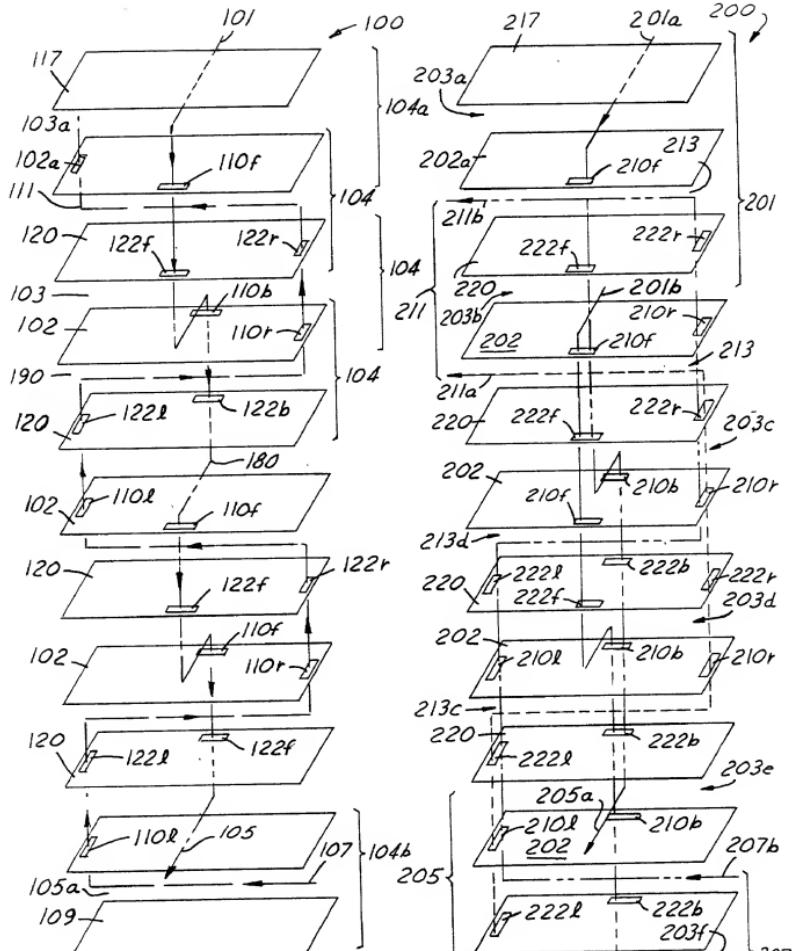


FIG.3

FIG. 4

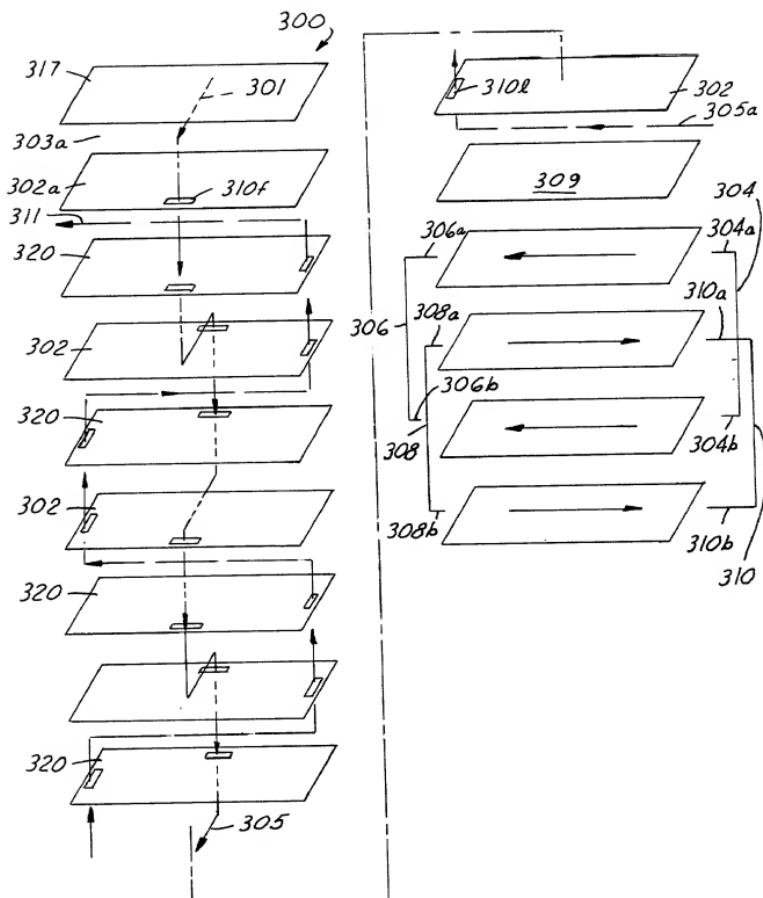


FIG.5

## DECLARATION AND POWER OF ATTORNEY - ORIGINAL APPLICATION

Attorney's Docket No.  
199-2106

As a below named inventor, I hereby declare:

My residence, post office address and citizenship are as stated below next to my name;

I verify believe I am the original, first and sole inventor or an original, first and joint inventor of the subject matter that is claimed and for which a patent is sought on the invention entitled

**IMPROVED PLATE-FRAME HEAT EXCHANGE REACTOR WITH SERIAL CROSS-FLOW GEOMETRY**

the specification of which is attached hereto.

I have reviewed and understand the contents of the specification identified above, including the claims.

I acknowledge my duty to disclose information of which I am aware that is material to the examination of this application in accordance with Section 1.56(a), Title 37 of the Code of Federal Regulations; and

as to application for patents or inventor's certificate on the invention filed in any country foreign to the United States of America, prior to this application by me or my legal representatives or assigns,

no such applications have been filed, or  
 such applications have been filed as follows

COUNTRY	APPLICATION NO.	DATE OF FILING (month, day, year)	DATE OF ISSUE (month, day, year)	PRIORITY CLAIMED UNDER 35 USC 119

I hereby claim the benefit under 35 U.S.C. § 120 of any United States application(s) or § 365(c) of any PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C. § 112, I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR § 1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application.

(Application Number)	(Filing Date)	(Status - patented, pending, abandoned)
(Application Number)	(Filing Date)	(Status - patented, pending, abandoned)

**POWER OF ATTORNEY:** As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the United States Patent and Trademark Office connected therewith and to act on my behalf before the competent International Authorities in connection with any and all international applications filed by me. (List name and registration number)

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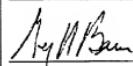
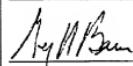
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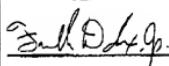
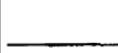
I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

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